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Palm-based biofuel refinery (PBR) to substitute petroleum refinery: An energy and emergy assessment

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ABSTRACT

As the most active palm industry cluster in the world, Malaysia produces enormous amount of biomass from the industry. This work studies the possibility of creating a renewable and sustainable source of energy by fully utilizing an area of land to provide liquid biofuel for the country. Palm-based biofuel refinery (PBR) proposed in this study has the ultimate goal to displace petroleum fuels and fulfill domestic energy demand. It fully utilizes indigenous palm biomass to fulfill 35.5% of energy demand in the country by using land area of only 8% of current palm cultivation. The operation concept of PBR is similar to petroleum refinery in which a single source feedstock (crude petroleum) can be processed to multiple products. In PBR, products from an oil palm plantation will be converted to various biofuel end products. Renewable biofuel such as biodiesel and bioethanol can be produced from crude palm oil and lignocellulosic residues. Energy and emergy assessment were made in this work to evaluate the sustainability and efficiency of PBR. Biofuel produced from PBR has a high energy equivalent of 31.56 MJ/kg as 1 ha of land can produce 182,142 MJ annually. Although there are still obstacles to be overcome, it is important for Malaysia to develop its own energy supply from indigenous resources as an initiative not only for security but also lower carbon emission.

Contents

1. Introduction

It has been a century since Rudolf Diesel ran his diesel engine with vegetable oil when development of biofuel is flourished in the last phase of petroleum age. In fact, biofuel has fixed the eyes of the world after the energy shock in the early 21st century. Detonation of energy crisis has aggrandized energy strategies in national policies to reduce the vulnerability of energy sector. The strong powers in the world are competing severely in the geopolitical chess game for the control of energy flows. At this moment, position on the chessboard is thus becoming the theme in the national energy policies. Adapting credible plans to reduce oil

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dependency principally could be pivotal for the country to maintain a sustainable development. As the most active palm industry area in the world, Malaysia holds the potential to utilize palm resources into renewable energy especially biofuel. In such a condition, development of technologies to convert palm oil into biodiesel and lignocelluloses into bioethanol are peppered with support and subsidy from the government.

Although several candidates are proposed, the systematic way to displace petroleum is remained controversial and much debated. Nevertheless, palm based biodiesel and lignocellulosic bioethanol with high viability in transportation system are still the main focus for Malaysia, since the country is bestowed with agricultural resources which can be turned into valuable biofuel. It is interesting to study the possibility of creating a renewable and sustainable source of energy by fully utilizing an area of land to provide liquid biofuel for the country. Due to geographical factor, Malaysia is able to produce large amount of palm oil which is raw material for biodiesel production. Palm oil has superior annual yield per hectare as compared to other oil-seeds [1]. Accompany with the mass production of palm oil, a great quantity of lignocellulosic residues is generated in plantation area and mills. This category of biomass was deemed to be excellent candidate for ethanol production since they contain fermentable sugars in polymeric forms such as cellulose and hemicelluloses. Moreover, the lignin obtained is suitable to be combusted for electricity generation. In this context, high amount of energy can be produced in relatively small area of land. With this key superiority in land area used, the capability of palm-based energy to displace fossil fuels is much higher than other crops which require a large area of land for cultivation. For example, to replace 10% of that energy value in the EU using biofuel obtained solely from rapeseed plantations, the land area devoted for biofuel have to be approximately 1.5 to 2 times of the whole land area of United Kingdom [2].

By incorporating and integrating both processes, a refinery with sole purpose of biofuel production can be designed. Palm-based biofuel refinery (PBR) is constructed with the ultimate objective to displace petroleum fuels and fulfill domestic energy demand. The production capacity of palm-based biofuel refinery (PBR) is predicted to fully supersede petroleum in Malaysia. The operation concept of PBR is similar to petroleum refinery in which a single source feedstock (crude petroleum) can be processed to multiple products. In PBR, products from an oil palm plantation will be converted to various biofuel end products. Whilst crude palm oil (CPO) is further processed into biodiesel through transesterification, residues collected from cultivation are crushed into smaller pieces for pretreatment and subsequently hydrolysis to obtain fermentable sugar and eventually bioethanol. In addition, the lignin separated from lignocelluloses can be combusted as fuel to generate electricity.

Despite of that, the environmentalists oppugn that plantation of oil palm would causes adverse effects to ecosystem. Hence, it is essential to perform a holistic evaluation to investigate the sustainability of palm-based biofuel refinery especially its consumption of both non-renewable (fossil fuels) and renewable resources (water, soils, labor and pollution). In this respect, energy and emergy analysis provides a conceivable picture of this visionary energy hub concept as well as an overview for environmental and social impact. The analysis may provide clues for questions regarding sustainability of PBR and investments in environmental protection.

In this manuscript, a concept of palm-based biofuel refinery was proposed and defined. The production capacity of PBR was calculated based on meter square of land area. The process of biofuel production was described with additional energy balance assessment and emergy synthesis. Finally, a discussion on the feasibility of PBR in Malaysia was carried out together with elucidation of sites selection.

2. Materials and methods

2.1. Assumptions

The latest issue raised by the oil palm critics is land-use change. However, by inspecting several types of popular oil crops today, the authors have found out that oil palm use the least area of land to produce high amount of oil and hence biodiesel, as summarized in Table 1. Table 1 also shows that oil palm plantation produces large quantity of lignocellulosic biomass for the production of bioethanol. This means large amount of carbon is sequestrated by oil palm in the form of biomass. Therefore, assuming that there are no new types of oil being developed in the near future, and no more lands are being utilized for agriculture, palm oil has the least effect on land-use change due to its high yield per hectare compared to rapeseed and soybean oil. In this study, land-use change is not taken into account considering that the oil palm plantation already exists eras ago.

2.2. Material balance

MPOB reported that Malaysia produces 17,734,439 tonnes of CPO from 4,487,957 ha of plantation in the year of 2008 [5]. On average, 1 ha of land in Malaysia is able to produce 3.95 tonnes of CPO annually. Due to maturity of related technology, it can be assumed that 99% of CPO is converted into palm methyl ester (PME) in PBR. In other words, 3911 kg of PME can be generated by 1 ha of land. A comparison is made with other oil crops in listed Table 1.

On the other hand, production of bioethanol largely depends on recovery of sugar (glucose and xylose) from cellulose and hemicellose. As shown in Table 2, most of the lignocellulosic biomass comes from oil palm fronds which contain high portion of cellulose (62%) and lower content of lignin (15%). Type of lignocellulosic feedstock in fact determines the efficiency of the conversion process. For biomass which has lower content of cellulose (40%) and higher amount of lignin (21%) such as corn residues, Demirbas reported that the conversion and recovery efficiency of cellulose to glucose is 0.76, whereas that of

Table 1
Biodiesel and bioethanol yield from different crops in 1 ha of land (assuming 99% of oil to methyl ester conversion).

Crops	Oil yield (t/ha/a)	Biodiesel yield (t/ha/a)	Bioethanol yield (t/ha/a)	Energy equivalent (MJ/ha)	References
Oil palm	3.95	3.91	1.86	206.27	[3,4]
Rapeseed	1.23	1.22	–	48.69	[2]
Soybean	0.40	0.40	–	15.96	[5]
Sunflower	0.95	0.94	–	37.52	[6,7]
Cotton seed	0.22	0.22	–	8.78	[8]
Jatropha	1.5–3.0	1.49–2.97	–	59.47	[9,10]
Sugar cane	–	–	11.35	306.45	This work
Corn	–	–	2.54	68.58	This work
Wheat	–	–	1.86	50.22	This work

Table 2
Quantity, composition and bioethanol production of palm residues compared with other crops and residues.

Types	Production (tonnes/ha)	MC (% wt)	Dry mass (tonnes/ha)	Energy content (J/g)	L (% dw)	α-C (% dw)	HC (% dw)	α-C (kg/ha)	HC (kg/ha)	BE (kg/ha)	L (kg/ha)	References for composition
Fronds	10.88 [5,31,32]	60.0	4.35	7,971 [37]	14.8	62.3	24.2	2711	1053	1035	644	[38]
EFB	4.44 [33,34]	65.0	1.55	18,960 [31]	17.6	54.4	28.0	845	435	348	274	[29]
Fibers	2.72 [33,34]	42.0	1.58	20,640 [31]	28.5	20.8	38.8	328	612	238	450	[30]
Shells	1.11 [33,34]	7.0	1.03	22,140 [31]	50.7	20.8	22.7	215	234	117	523	[31]
Trunks	2.52 [31,35]	75.9	0.61	16,869	17.1	41.2	34.4	250	209	121	104	[21]
Total	1,859	1,350										
Sugarcane	81.0 [11]	–	17.0 [13]	–	–	–	–	–	–	8,500	–	–
Sugarcane bagasse	–	–	10.2 [13]	–	–	–	–	–	–	2,856	–	–
Corn	5.40 [12]	–	3.70 [13]	–	–	–	–	–	–	1,467	–	–
Corn stover	–	–	3.70 [13]	–	–	–	–	–	–	1,073	–	–
Wheat	–	–	2.40 [13]	–	–	–	–	–	–	960	–	–
Wheat straw	–	–	3.12 [13]	–	–	–	–	–	–	905	–	–

L, Lignin; α-C, α-Cellulose; HC, Hemicellulose; BE, Bioethanol, %dw, % dry weight.

hemicelluloses to xylose is 0.90 by using concentrated sulfuric acid hydrolysis on cornstalk [13,14]. The paper also claims that fermentation efficiencies of glucose and xylose to ethanol can go up to 0.75 and 0.50 respectively. In this work, these values are adapted conservatively due to the lack of studies on production of glucose from oil palm biomass. Therefore, the yields of SGB from oil palm residues especially oil palm fronds are basically predicted to be significantly higher than the values estimated in this work. Fermentation of glucose and xylose to ethanol can be represented with the Equations (1) and (2). According to the equations, bioethanol stoichiometry yields for glucose and xylose are 0.5111 and 0.5175 respectively. By using Equations (4) and (5), capacity of bioethanol production from lignocellulosic materials can be computed. Material balance is calculated as illustrated in Table 2. As a comparison, production of bioethanol from other crops in 1 ha of land is investigated and listed in Table 1.

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \quad (1)$$

$$3C_5H_{10}O5 \rightarrow 5CH_3CH_2OH + 5CO_2 \quad (2)$$

$$\text{Bioethanol yield} = \text{material(tonnes)} \times \text{theoretical yield} \times \text{glucose recovery efficiency} \times \text{fermentation efficiency} \quad (3)$$

$$\text{Bioethanol from cellulose(tonnes)} = \text{cellulose(tonnes)} \times 0.5111 \times 0.76 \times 0.75 \quad (4)$$

$$\text{Bioethanol from hemicellulose(tonnes)} = \text{hemicellulose(tonnes)} \times 0.5175 \times 0.90 \times 0.50 \quad (5)$$

2.3. Energy analysis

The study of energy and material balance in PBR is performed by considering all of the raw materials and products, leading from production and processing of raw materials to biofuel as end products. Input material flows are converted to energy flows by multiplication with energy equivalents. Table 2 shows the energy analysis for the whole system of PBR including the main stages of the linear production chain as well as feedback flow. Energy flow is calculated based on energy equivalent of each item by using Equation (6):

$$\text{Energy(J)} = \text{Mass(unit)} \times \text{Energy equivalent(J/unit)} \quad (6)$$

Energy balance assessment is conducted within the system boundary, including direct and indirect energy flow by using the basic unit of 1 ha of land. In this study, all side products are fully recovered for steam and electricity generation.

2.4. Emergy synthesis

Emergy synthesis demonstrates the ability of a system to survive and organize in hierarchies by utilizing energy at highest efficiency in terms of power generation. It is given the definition of "the total available energy (exergy) of one kind (usually solar) directly and indirectly used up to drive a process and generate a product or a product flow" [15]. As a complement to other existing analysis methods, emergy assessment provides adequate consideration of ecological processes to human progress and wealth. In this study, emergy synthesis connects the economic and ecological systems in quantity of solar energy as an objective basis to provide an ecocentric and holistic evaluation [16]. The contribution of ecosystems and society to the system, which can be considered as "environmental cost" and "social cost", is taken into consideration which cannot be evaluated in energy or exergy analysis solely. In fact, emergy is a donor-based system which gives totally different information with receiver based systems. In this approach, all inputs which are either in the form of energy, matter, human work or nature work are expressed in equivalent solar energy. These direct and indirect inputs of the system (including nature contributions and purchased resources) are taken into consideration. By using equivalent solar unit, the impact from different sources can be evaluated and compared on a similar basis. This joint analysis of economic and ecology implications provide a new perspective in evaluation. However, emergy is not an anthropocentric concept. It does not evaluate an object according to its value to humanity. In contrast, it provides a more ecocentric view from environmental aspect. Despite of this drawback, emergy synthesis still plays a role as a complementary method to assess the sustainability of PBR, from the view of donor side (the nature). For biorefinery case, resources such as solar energy and soil fertility are provided by nature through biosphere cycles. Unit used to measure emergy is solar equivalent energy (seJ). Emergies of each process/stage/items are calculated through Equation (7) below:

$$\text{Emergy(seJ)} = \text{Unit} \times \text{Transformity(seJ/unit)} \quad (7)$$

Emergy evaluation is made based on energy and mass analysis in the early section using "solar transformity" (seJ/unit) as conversion factor. Total biosphere investment in PBR can be ascertained by summing up emergies of all inputs. Fig. 1 shows the system diagram of emergy flows in the system including all necessary inputs of materials, energy and human services.

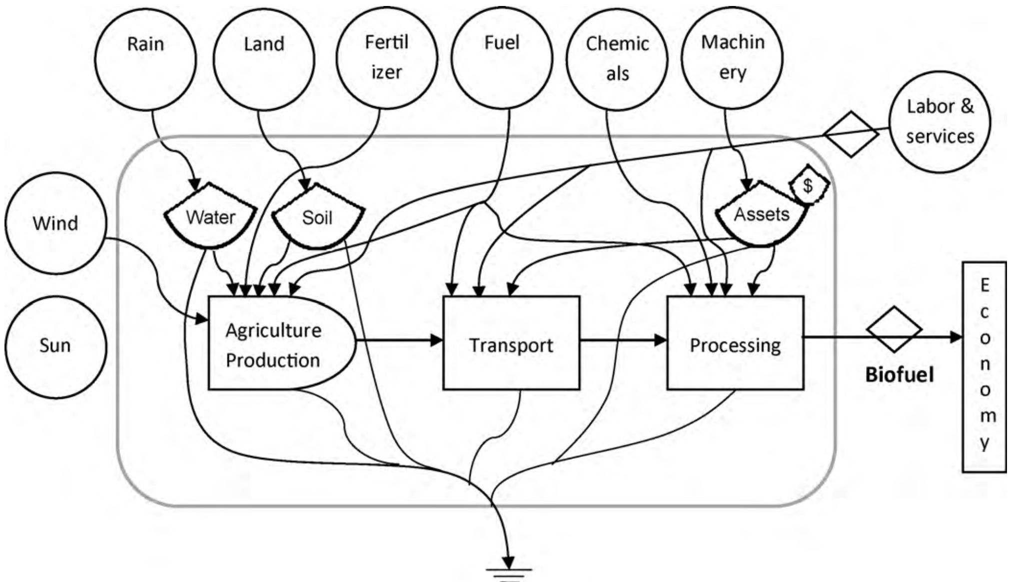

Fig. 1. System diagram of emergy flows in the system including all necessary inputs of materials, energy and human services.

Emergy-based performance indicators are evaluated to compare different uses of the same resource or different processes yielding the same kind of output [17]. The indicators are calculated according to Equations (8), (9), (10) and (11) where R represents renewable, N represents non-renewable, F represents imported and Y represents total emergy. In this context, solar radiation is completely renewable; diesel fuel is considered completely nonrenewable; flows supported by the economic system are partly renewable [18]. Labor and services can be considered as having the same fraction of renewable resources (which indirect contribute to the total emergy flow) of the respective country [19]. For examples, economic systems like China, Italy, Brazil and Australia have proportion of 26%, 6%, 50% and 49% respectively for the share of renewable driving the systems [18–20]. For Malaysia, renewable shares 25.84% of total emergy used [20].

Emergy Investment Ratio (EIR) compares the ratio of economic resources purchased to natural resources. When the process becomes more energy intensive, natural contribution would become proportionately lesser.

$$\text{Emergy Investment Ratio(EIR)} = \frac{F}{N + R} \qquad (8)$$

Emergy yield ratio (EYR) is a measure of the process ability to exploit the locally available resources. Indeed, EYR is analogous to Hall's energy return on energy invested (EROI) with additional parameters such as input from environment (soil and water) and human service inputs purchased from the economy, which can be further divided into renewable and non-renewable resources. Processes EYR higher than unity provide significant net emergy to the economy. In other words, these processes provide growth

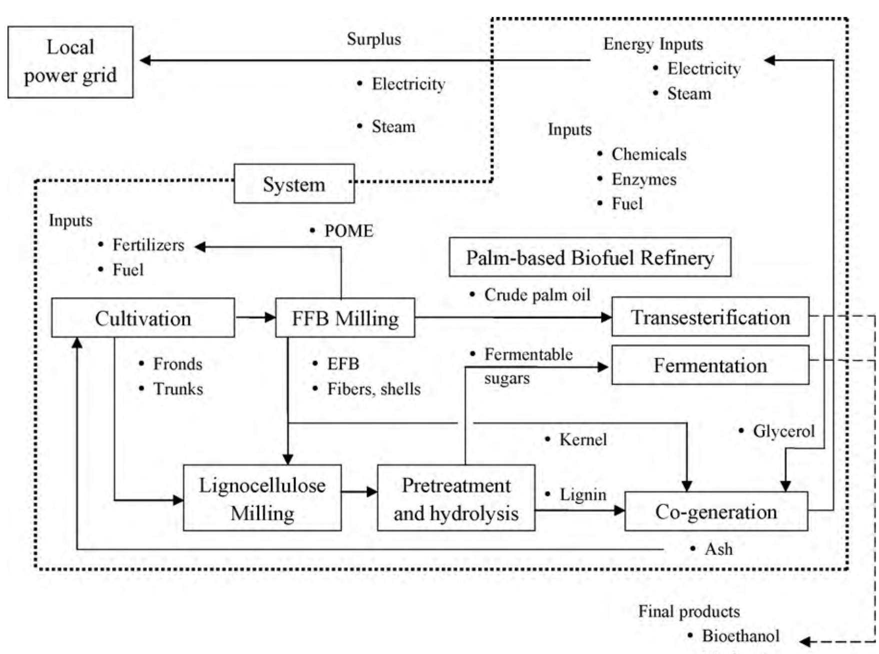

Fig. 2. Block flow diagram of palm-based biofuel refinery (PBR) and system boundary.

opportunities to the system. EYR is calculated from the following equation:

$$\text{Emergy Yield Ratio(EYR)} = \frac{Y}{F} \tag{9}$$

ELR and ESI are calculated based on renewable fraction of inputs emergy flow. ELR is a measure of amount of non-renewable and purchased emergy proportionate to the amount of locally renewable resources. Local renewable emergy is the driving force to support an ecosystem within the constraints imposed by the environment. Addition of non-renewable and imported emergies is indicated by the ELR value to detect possible disturbance to the local environmental dynamics. A high ELR represents a more intensive possible environmental impact. In order to measure interaction with both local environment and renewability, EYR (import versus local) and ELR (non-renewable versus renewable) are combined as Emergy Sustainability Index (ESI).

$$\text{Environmental Loading Ratio(ELR)} = \frac{N+F}{R} \tag{10}$$

$$\text{Emergy Sustainability Index(ESI)} = \frac{\text{EYR}}{\text{ELR}} \tag{11}$$

3. System boundary

The first stage of biofuel production in PBR is plantation (agricultural). For biodiesel production, the process is divided into

Table 3
Energy analysis of PBR on 1 ha basis.

Item	Quantity	Unit	Energy equivalent (MJ/unit)	References for energy equivalent	Energy (MJ/ha/year)	% of total energy used
Plantation						
Seeds [56]	168	kg/ha/year	0.99	[42]	166	0.13%
Diesel consumption for transportation		ha/year	2,368	[43]	2,368	1.82%
Fertilizers: Nitrogen (N) [57]	76	kg/ha/year	57.47	[44]	5,570	4.28%
Fertilizers: Phosphorus (P_2O_5) [57]	86	kg/ha/year	7.04	[44]	1,152	0.89%
Fertilizers: Potassium (K_2O) [57]	119	kg/ha/year	6.40	[45]	762	0.59%
Subtotal	10,018	7.70%				
Milling processes						
Steam [58]	14,731	kg/ha/year	2.60	[11]	38,300	29.42%
Electricity		ha/year	1,053	[46]	1,053	0.81%
Diesel (For boilers and vehicles) [59]	10	l/ha/year	42	[47]	420	0.32%
Subtotal	39,773	30.56%				
Transesterification						
Steam		ha/year	5,426	[48]	5,426	4.17%
Electricity		ha/year	0.012	[48]	0.012	0.00%
Methanol [21]	718	kg/ha/year	30.29	[49]	21,754	16.71%
Sodium hydroxide [21]	10	kg/ha/year	6.28	[50,18]	63	0.05%
Subtotal	27,243	20.93%				
Lignocellulose milling						
Electricity		ha/year	1,469	[23]	1,469	1.13%
Subtotal	1,469	1.13%				
Dilute acid pretreatment						
Electricity		ha/year	1,295	[13]	1,295	0.99%
Steam		ha/year	27,350	[13]	27,350	21.01%
Sulfuric acid (1.1%)	684	kg/ha/year	1.10	[13]	750	0.58%
Lime (10M)	498	kg/ha/year	3.47	[13]	1,728	1.33%
Subtotal	31,123	23.91%				
Hydrolysis and fermentation						
Electricity		ha/year	14,543	[13]	14,543	11.17%
Ammonia (For enzymes)	1.42	kg/ha/year	784.58	[13]	1,113	0.86%
Subtotal	15,656	12.03%				
Product recovery, cooling water and effluent treatment						
Electricity for distillation		ha/year	3,876	[13]	3,876	2.98%
Cooling water		ha/year	611	[13]	611	0.47%
Electricity for effluent treatment		ha/year	398	[13]	398	0.31%
Subtotal	4,885	3.75%				
Energy recovery						
Released biogas		ha/year	17,431	[22]	17,431	16.44%
Glycerol [21]	704	kg/ha/year	25.07	[51]	17,649	16.65%
Palm kernel (46.6% of oil) [12]	1,020	kg/ha/year	30.46	[52,31]	31,069	29.30%
Burnt lignin	1,350	kg/ha/year	29.54	[53]	39,879	37.61%
Subtotal	106,028	100.00%				
Output						
Palm methyl ester	3,911	kg/ha/year	39.91	[54]	156,088	75.67%
Ethanol	1,859	kg/ha/year	27	[55]	50,193	24.33%
Subtotal	206,281	100.00%				
Total fossil energy requirement (MJ/ha/year)						24,139
Energy output (MJ/ha/year)						206,281
Net energy produced by 1 ha of land (MJ/ha/year)						182,142
Energy equivalent of biofuel produced (MJ/kg):						31.56

two stages, which are palm fruits milling and transesterification. On the other hand, production of bioethanol has to go through four stages which are lignocellulose milling, pretreatment, hydrolysis and fermentation. Fig. 2 illustrates the system boundary used in this work. In stage of agriculture, fresh fruit bunches (FFB) is the final product. The production of FFB involves planning, nursery establishment, site preparation, field establishment, field maintenance, harvesting, collection and replanting [1]. Then, transestrification requires chemical processes and separations. For bioethanol, the lignocellulosic biomass is first collected and milled to small pieces. Next, thermal and chemical pretreatments take place to remove lignin. The final stages involve biological processes (fermentation) and separation (product recovery). Due to the theme of PBR, most of the co-products such as lignin, kernel and glycerol will be consumed for energy purpose. Part of the nutrient rich-biomass is utilized as fertilizer to minimize the energy input for cultivation. The calculations are based on 1 hectare (ha) per year of oil palm cultivation.

4. Results

As demonstrated in Table 1, oil palm residues comprise of high portion of holocellulose. Holocellulose is defined as the total polysaccharide fraction of lignocellulosic biomass which is composed of cellulose and all of the hemicelluloses. The capacity of bioethanol that can be produced from each category of waste from PBR in Malaysia is estimated to be 1859 kg/ha. For the case of PME, by assuming 99% of CPO is converted to PME, 3911 kg of PME can be generated by 1 ha of land.

Table 2 shows the energy analysis in each process to produce biofuel per ha. In plantation stage, 10,018 MJ was spent for fertilizers, seeds and diesel in 1 ha of land yearly. The following stage, which is milling of FFB to CPO, records the highest energy consumption at 30.56% or 39,773 MJ/ha. The major component in this category is steam used for heating purpose in extractions and distillations of oil. However, transesterification of CPO to PME also holds about one fifth of total energy consumption (27,243 MJ/ha/

Table 4
Emergy analysis of PBR (agriculture phase) on 1 ha basis.

Item	Quantity	Unit	Transformity (seJ/unit)	References for transformity	Emergy (seJ/ha/year)	% of total emergy used
Nature contribution						
Local renewable resources						
Solar radiation [60]	6.94E+13	J/ha/year	1.00E+00	Definition	6.94E+13	0.42%
Rain (Chemical potential)[a]	1.24E+11	J/ha/year	3.06E+04	[66]	3.79E+15	22.76%
Evapotranspiration (ET)[b]	5.93E+10	J/ha/year	3.06E+04	[66]	1.81E+15	10.89%
Local non-renewable resources						
Net topsoil loss (Organic matter)[c]	1.85E+09	J/ha/year	2.25E+05	[63]	4.16E+14	2.50%
Subtotal	6.09E+15	36.56%				
Purchased resources						
Feedstock from economy resources						
Seeds	9.90E+05	J/ha/year	1.63E+04	This work	1.61E+10	0.00%
Fertilizer: Nitrogen (N)[d]	7.60E+04	g/ha/year	6.38E+09	[15]	4.85E+14	2.91%
Fertilizer: Phosphorus (P_2O_5)[d]	8.60E+04	g/ha/year	6.55E+09	[15]	5.63E+14	3.38%
Fertilizer: Potassium (K_2O)[d]	1.19E+05	g/ha/year	1.85E+09	[15]	2.20E+14	1.32%
Subtotal	1.27E+15	7.61%				
Labor and services (L & S)						
Herbicides, pesticides & fertilizers [64,65]	144	$/ha/year	1.79E+13	[20]	2.58E+15	15.46%
Labor [64,65]	308	$/ha/year	1.79E+13	[20]	5.51E+15	33.07%
Machinery and assets[f]	68	$/ha/year	1.79E+13	[20]	1.22E+15	7.30%
Subtotal	9.31E+15	55.84%				
Products						
Crude palm oil[e]	3.95E+06	g/ha/year				
	1.59E+11	J/ha/year				
Palm residues[e]	9.11E+06	g/ha/year				
	2.94E+11	J/ha/year				
Total palm biomass[f]	4.53E+11	J/ha/year				
Total emergy (w/o L & S)	7.36E+15	44.17%				
Total emergy (with L & S)	1.67E+16	100.00%				
Transformity of palm biomass (w/o L & S)[g,h]	1.63E+04					
Transformity of palm biomass (with L & S)	3.68E+04					
Specific emergy of palm biomass (w/o L & S)	5.64E+08	seJ/g				
Specific emergy of palm biomass (with L & S)	1.28E+09	seJ/g				

[a] Energy of rain = (Average rainfall) × (Area) × (Density) × (Gibbs free energy) = 2.5 m/year × 10,000 m^2/ha × 1000 kg/m^3 × 4940 J/kg = 1.24E + 11 J/ha/year; Average rainfall in Malaysia = 2.5 m/year [60].

[b] Energy of ET = (Average ET) × (Area) × (Density) × (Gibbs free energy) = 1.2 m/year × 10,000 m^2/ha × 1000 kg/m^3 × 4940 J/kg = 5.93E + 10 J/ha/year; Average ET rate in oil palm catchment = 1.2 m/year [61].

[c] Energy of net topsoil loss = (Soil loss) × (Organic matter content) × (Energy content) = 6.5 tons/ha/year × 0.0195 × 1.46E + 10 J/tons = 1.85E + 09 J/ha/year; Average soil loss = 6.5 tons/ha/year; Average soil organic matter content in Malaysia oil palm cultivation = 1.95% [62]; Energy content = 14.6 GJ/tons [63].

[d] This work (Refer to Table 3).

[e] Energy content of palm biomass = ∑amount of palm residues or CPO produced × energy content. Calorific value of CPO = 40.14 MJ/kg; Energy content of palm residues listed in Table 2; amount of CPO and residues were taken from Table 1 and Table 2 respectively.

[f] Palm biomass in this case includes CPO, empty fruit bunch, fronds, shells, fibers and trunks.

[g] Transformity = Total emergy/Total energy of palm biomass.

[h] L & S indicate "Labor and Services".

year). On the other hand, production of bioethanol from lignocellulose spends 40.82% of total energy used. Similarly, the major spender in this case is steam. By-products such as lignin and palm kernels are employed in co-generation to generate electricity (106,028 MJ/ha/year) for PBR. By recovering portion of energy from biomass, the net fossil energy input is reduced to 24,139 MJ/ha/year. PME and ethanol produced from 1 ha of cultivation provides an energy output of 206,281 MJ/year. Energy equivalent of biofuel produced can be up to 31.56 MJ/kg in PBR.

Tables 3 and 4 demonstrate the emergy synthesis of PBR, while Table 5 provides information of renewable and non-renewable fractions in each stage. Fig. 3 represents the "emergy signature" of PBR in bar chart format. As shown in this diagram, labor and services have the largest share (48.99%) in emergy input of PBR, followed by machinery (22.08%) and chemical used in mill (13.60%). Emergy flows with proper consideration of renewable and non-renewable components as well as emergy-based performance indicators are computed as shown in Table 6 and Table 7, respectively [36,39–41].

5. Discussion

As shown in Table 2, the energy equivalent of biofuel produced from PBR has a high value of 31.56 MJ/kg as 1 ha of land can produce 182,142 MJ of energy annually. From different literature source, biodiesel produced from palm oil records 23.68 MJ/kg and 22.01 MJ/kg [1,21]. For lignocellulosic bioethanol, energy equivalent values found were 18.93 MJ/kg from hard woodchips and 114.58 MJ/kg from corn stover [22,23]. This indicates that by incorporating production of biodiesel and lignocellulosic bioethanol together, the net value of energy obtains from 1 ha of land is considerably high. However, due to inadequate data in process of lignocellulosic bioethanol production provided by the literature, the result should hold a slightly plus or minus to compensate certain assumptions made. Nonetheless, this result lends an insight on the efficiency and sustainability of palm-based biofuel refinery. Output/input energy ratio of biofuel from PBR is essentially larger than 1 (the value is 1.58), which means that it is still sustainable. In the year of 2007, the transportation sector in Malaysia consumed a total amount of energy accumulating to 6.58×10^7 GJ or 35.5% of the country's total energy demand [24]. By PBR's concept, biofuel produced from 361,257 ha of palm cultivation (which is only 8% of total palm cultivation in Malaysia) is sufficient to supply this amount of energy. By implementing biofuel refinery in palm industry, 19% of the total CO_2 emissions from fossil fuel in Malaysia could be avoided. Therefore, PBR not only provides energy security but also a cleaner environment. Furthermore, thousands of job opportunities would be created from the industry.

Nevertheless, the problem of PBR is revealed by emergy synthesis. Transformity of biofuel from PBR is found to be 4.92E + 05 seJ/J, which is higher than many other energy carriers. Ethanol produced from wheat in China, corn in Italy and switch grass in Iowa has transformity of 1.32E + 05 seJ/J, 9.92E + 04 seJ/J and 1.10E + 05 seJ/J respectively [18,25]. It was also reported that transformity of biodiesel converted from soybean oil is 1.60E + 05 seJ/J [26]. The major cause of this high transformity is due to relatively high national emergy money ratio of Malaysia, which is 1.79E + 13 seJ/$. Compared to only 1.93E + 12 seJ/$ in

Table 5
Emergy analysis of PBR (biofuel refinery phase) on 1 ha basis.

Item	Quantity	Unit	Transformity (seJ/unit)	References for transformity	Emergy (seJ/ha/year)	% of total emergy used
Palm biomass from agriculture phase (w/o L & S)[a]	1.31E+07	g/ha/year	1.63E+04	This work	0.00E+11	0.00%
Palm biomass from agriculture phase (with L & S)[a]	1.31E+07	g/ha/year	3.68E+04	This work	3.90E+11	0.00%
Water used in ethanol production[b]	2.50E+08	J/ha/year	6.89E+04	[67]	1.72E+13	0.02%
Subtotal	1.74E+13	0.02%				
Purchased resources						
Feedstock from economy resources						
Net electricity input[a]	2.41E+10	J/ha/year	3.36E+05	[15]	8.11E+15	8.03%
Methanol[a]	7.18E+05	g/ha/year	7.23E+09	[68]	5.19E+15	5.14%
Sodium hydroxide[a]	1.00E+04	g/ha/year	6.38E+09	[15]	6.38E+13	0.06%
Sulfuric acid[a]	6.84E+05	g/ha/year	6.38E+09	[15]	4.36E+15	4.32%
Lime[a]	4.98E+05	g/ha/year	1.73E+09	[15]	8.62E+14	0.85%
Ammonia (for enzymes)[a]	1.42E+03	g/ha/year	2.87E+09	[15]	4.08E+12	0.00%
Enzymes (bioethanol) [69]	311	$/ha/year	1.79E+13	[20]	5.57E+15	5.52%
Subtotal	7.43E+16	23.93%				
Labor and services (L & S)						
Labor, supplies, overhead (biodiesel) [70]	680	$/ha/year	1.79E+13	[20]	1.22E+16	12.05%
Machinery and assets (biodiesel)[c]	1,156	$/ha/year	1.79E+13	[20]	4.14E+15	4.10%
Labor, supplies, overhead (SGB) [72]	2,240	$/ha/year	1.79E+13	[20]	4.01E+16	39.70%
Machinery and assets (SGB)[d]	5,793	$/ha/year	1.79E+13	[20]	2.07E+16	20.53%
Subtotal	7.71E+16	76.38%				
Products						
PME produced[e]	3.91E+06	g/ha/year				
Ethanol produced[e]	1.86E+06	g/ha/year				
Total biofuel produced[f]	2.06E+11	J/ha/year				
Total emergy (w/o L & S)	2.42E+16	23.94%				
Total emergy (with L & S)	1.01E+17	100.00%				
Transformity of biofuel (w/o L & S)	1.17E+05					
Transformity of biofuel (with L & S)	4.92E+05					
Specific emergy of biofuel (w/o L & S)	4.19E+09	seJ/g				
Specific emergy of biofuel (with L & S)	1.76E+10	seJ/g				

[a] This work (Refer to Table 1). Palm biomass in this case includes CPO, empty fruit bunch, fronds, shells, fibers and trunks.
[b] Energy of water = amount of water × Gibbs energy = 5.07E + 07 g × 4.94 J/g; 5.57 tons of water is required for 1 ton of lignocelluloses to produce bioethanol [18,75].
[c] 5 years of life span is assumed [71].
[d] 5 years of life span is assumed [73].
[e] This work (Refer to Table 1).
[f] Biofuel in this case indicates PME and ethanol.

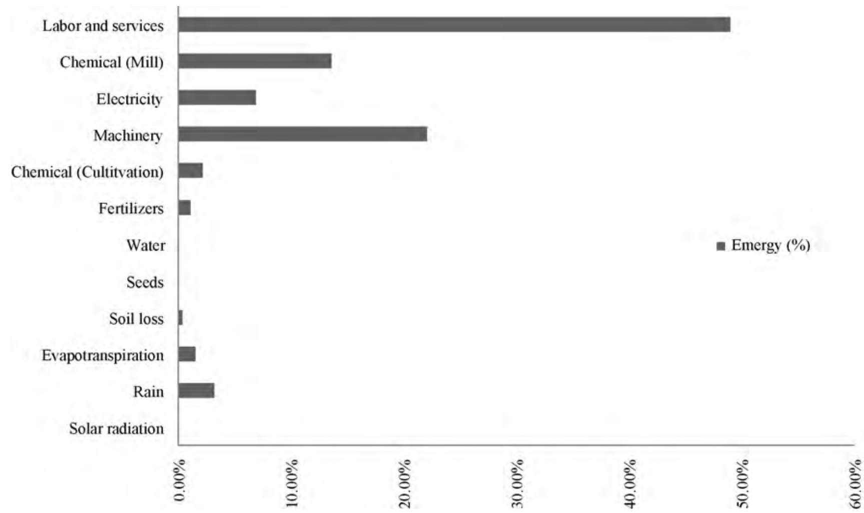

Fig. 3. Emergy signature of PBR.

United States, PBR would obtain a transformity of only 1.34E + 05 seJ/J if Malaysia has the same national emergy money ratio as United States. However, the situation is still not optimistic as fossil fuels have nearly one degree of lower transformity compared to biofuel. Diesel, coal, natural gas and crude oil possess respectively transformity of 1.11E + 05 seJ/J, 6.71E + 04 seJ/J, 8.05E + 04 seJ/J and 0.07E + 04 seJ/J [15].

On the other hand, EYR decreased from 1.58 to 1.05 from agriculture phase to biofuel production phase. In other words, most of the economical resources inputs to PBR are added during the milling of biomass into biofuel. EYR of PBR is as low as the other biofuel, which is 1.05, not far from 1.29 for switchgrass, 1.24 for wheat ethanol and 1.14 for corn ethanol [18,25]. The ability to exploit local resources for biofuel is still very low comparing with non-renewable energy. This has unveiled that production of biofuel actually transforms resources that are already available from previous processes and do not create any growth for the system. In fact, the nature is more efficient in creating energy carrier than human technology at this moment. Extraction of fossil fuel (EYR ranged from 3 to 7) provides a better means of exploitation of local resources.

However, biofuel commits much lesser disturbance to the local environmental dynamics as compared to fossil fuel. In order to investigate this factor, ELR is computed and a result of 3.02 is obtained. In reality, crude oil has ELR as high as 1429.3 [27]. This might be one of the key advantages of biofuel over fossil fuel. From literature, ELR of ethanol from switch grass in Iowa, wheat in China and corn in Italy are 3.87, 4.05 and 17.65 respectively [18,22,28]. As a comparison, ELR of a large-scale hydroelectric power plant proposed for the Mekong River in Thailand is 3.3 [27]. In this respect, PBR results in lesser adverse effects to environment than some other types of renewable energy. An interesting result was found for EIR of PBR, which is only 0.95. This EIR is much lower compared to EIR of switch grass ethanol (3.42) [25]. In other words, less emergy is required from environment to extract 1 unit of free emergy from the environment through the conversion of biomass into biofuel. Clearly from this case, although this EIR is not as low as that of crude oil (0.07), but it does provides a higher return on investment among the energy themed biorefineries [25]. From the emergy synthesis conducted, the largest portion of emergy inputs come from labor and services. Therefore, biofuel from PBR is actually expensive in terms of “social cost”. The relatively high cost

Table 6
Renewable and non-renewable fraction of emergy flows.

Item	Value (seJ/ha/year)	Renewable fraction	Non-renewable fraction
Agricultural phase			
Local renewable input, R_L	5.67E+15	5.67E+15	0.00E+00
Local non-renewable input, N_L	4.16E+14	0.00E+00	4.16E+14
Purchased resources (agricultural phase), F_A	1.27E+15	0.00E+00	1.27E+15
Labor and services (agricultural phase), S_A	9.31E+15	2.41E+15	6.90E+15
Total renewable emergy inputs to agricultural phase, R_A	–	8.08E+15	–
Total non-renewable emergy inputs to agricultural phase, N_A	–	–	8.59E+15
Total emergy inputs to agricultural phase, Y_A	1.67E+16	8.08E+15	8.59E+15
Biofuel production phase			
Purchased resources (biofuel production phase), F_B	2.42E+16	1.44E+15	2.28E+16
Labor and services (biofuel production phase), S_B	7.71E+16	1.99E+16	5.72E+16
Total renewable emergy inputs to biofuel production phase, R_B	–	2.13E+16	–
Total non-renewable emergy inputs to biofuel production phase, N_B	–	–	8.00E+16
Total emergy inputs to biofuel production phase, Y_B	1.01E+17	2.13E+16	8.00E+16
PBR			
Total purchased resources, F_T	2.55E+16	1.44E+15	2.41E+16
Total labor and services, S_T	8.64E+16	2.23E+16	6.41E+16
Total emergy inputs to PBR, $Y_T = Y_A + Y_B$	1.18E+17	2.93E+16	8.86E+16
Total renewable emergy inputs, $R_T = R_L + R_A + R_B$	–	2.93E+16	–
Total non-renewable emergy, $N_T = N_L + N_A + N_B$	–	–	8.86E+16

Table 7
Emergy-based indicators for PBR.

Item	Units	Value
Energy and mass flow		
Total commercial energy invested in PBR	J/ha/year	2.41E+10
Biomass produced	J/ha/year	4.53E+11
Biofuel produced	g/ha/year	5.77E+06
Energy content of biofuel produced	J/ha/year	2.06E+11
Net energy yield of biofuel (energy of biofuel–energy invested)	J/ha/year	1.82E+11
Biomass production		
Transformity of biomass, without labor and services	seJ/J	1.63E+04
Transformity of biomass, with labor and services	seJ/J	3.68E+04
Specific emergy of biomass, without labor and services	seJ/g	5.64E+08
Specific emergy of biomass, with labor and services	seJ/g	1.28E+09
Total emergy inputs, Y_A	seJ/ha/year	1.67E+16
EYR of biomass = $Y_A/(F_A+S_A)$		1.58
ELR of biomass = N_A/R_A		1.06
Empower density of biomass = Y/Area	seJ/m^2	1.67E+12
ESI of biomass = EYR/ELR		1.49
Biofuel production		
Energy cost of biofuel	J/g	3.16E+04
Output/input energy ratio of biofuel		1.58
Transformity of biofuel, without labor and services	seJ/J	1.17E+05
Transformity of biofuel, with labor and services	seJ/J	4.92E+05
Specific emergy of biofuel, without labor and services	seJ/g	4.19E+09
Specific emergy of biofuel, with labor and services	seJ/g	1.76E+10
Total emergy inputs, Y_T	seJ/ha/year	1.18E+17
EIR = $(F_T+S_T)/(N_T+R_T)$		0.95
EYR = $Y_T/(F_T+S_T)$		1.05
ELR of biofuel = N_T/R_T		3.02
Empower density of biofuel = Y/Area	seJ/m^2	1.18E+13
ESI of biofuel = EYR/ELR		0.35

of production especially expenses in labor and machinery in fact affects the sustainability of biofuel. There are still obstacles in excogitation of new technologies to simplify and optimize the production process.

By inspecting the energy and emergy inputs distribution, some inputs can actually be mitigated through a proper planning. To reduce energy and emergy inputs in transportation, palm-based biofuel refinery should be located near to palm cultivation. Storage facilities for biofuel should be built within a fixed range from PBR. Apart from that, pipelines should be considered for short range transportation. In the same time, a proper planned wastewater treatment plant should be constructed to lower the emergy consumption in line with the theme of sustainable development. Palm oil mill effluent which is rich in nutrients is still awaited for better utilization when new related technologies are discovered. For instance, it can be used as fertilizers for cultivation as well as medium for growth of methane and hydrogen synthesis microbes [30]. Besides that, recently there are new approaches in transesterification without using methanol [74]. Methanol is unlikely a good raw material for biofuel since it is derived from fossil fuel. It shares a significant percentage of energy and emergy inputs in PBR. Therefore, by application of new methods without using methanol would further reduce the transformity and ELR of PBR. Technologies, especially genetic engineering would become the backbone of bioenergy industry to harness renewable resources in a much more efficient manner.

6. Conclusion

Turbulence in future energy sector would have driven the world to another epoch-making revolution which a transition stage would be crucial before meeting a breakthrough. No doubt, renewable biofuel would play an important role in this stage as long as energy security is met when petroleum is used up. Palm-based biofuel refinery provides an alternative for Malaysia as a reliable energy supply. As Malaysia is very experienced in palm cultivation, palm biomass would be an appropriate source for biofuel in the country. By fully utilizing of this indigenous biomass, 35.5% of national energy consumption can be secured by using land area of only 8% of current palm cultivation. Energy and emergy assessment made in this work would provide insight for researchers to improve the process at specific stage (such as methanol consumption and POME utilization). Although ESI is low for biofuel from crops, PBR still is a good option for the country as a start in preparing the upcoming energy tension. In fact, until today, there is still lack of truly sustainable sources of energy. However, it is essential for the country to develop its own energy supply based on indigenous resources as an initiative to face the challenges of energy crisis in the new era.

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